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William S. Saric

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14. ABSTRACT
The Mach 6 Quiet Tunnel (M6QT), the hypersonic low-disturbance facility formerly at NASA Langley, has been permanently installed as part of the Texas A&M National Aerothermochemistry Laboratory (TAMU-NAL) in College Station, Texas. The tunnel now operates interchangeably with the Adaptively Controlled Expansion Mach 5-8 tunnel (ACE) in a blowdown configuration with a maximum runtime of approximately 50 seconds. An initial series of tests to determine the quiet-flow capabilities of the nozzle indicate performance largely consistent with its former operation at NASA Langley, with evidence of a full-length quiet test core at stagnation pressures up to 145 psia. Intermittency present in the pressure signals at total pressures above 80 psia is quantified and discussed. In addition, the capability of the tunnel to support future flared-cone experimental models is demonstrated.

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"Experiments on transition physics in hypersonic boundary layers: Validation data for modeling and computations"

June 2010 – May 2011

Final Report: June 2010 through May 2011

- 6/2010-8/2010
    - Hofferth internship at NASA Langley under Steve Wilkinson & Catherine McGinley
        - Information sharing on broad range of M6QT-relevant topics: facility operation, nozzle cleaning & polishing, traversing mechanism design, hotwire anemometry & data reduction, hotwire probe fabrication & repair, etc.
        - Traverse mechanism fully designed and procured
- 8/2010-9/2010
    - Hofferth returns to TAMU, arranges to begin recommended cleanliness improvement in M6QT lab as first step to restarting experiments.
    - Major lab-wide cleanup effort persists for several weeks
- 9/2010-10/2010
    - M6QT test section removed, stripped (via sandblasting & pressure washing) and repainted using a sprayed-on, hard two-part epoxy better suited to high-temperature vacuum conditions than the previous Rustoleum paint.
    - Test section reinstalled.
    - Following reinstallation, first test of restored system is a vacuum-only leak test, with the ejectors operated with the incoming-air line closed upstream of the settling chamber. During this test, unexpected remnant sandblasting grit is extracted from the interior seams in the test section and blown forward into the nozzle as air re-enters the settling chamber. Test section is filled with floating fine dust following the run. Inspection of the nozzle throat region reveals rather severe contamination, with many very fine particles either stuck to or embedded in this most critical region of the nozzle. All run plans stop as discussions begin on how to properly address this issue.
    - Several light, non-contact methods are tried to clean the nozzle surface, without success.
- 11/2010
    - Detailed discussions with Steve Wilkinson at NASA Langley regarding the nozzle's history of fabrication, plating, and polishing efforts. Through these discussions, it is recommended that the nozzle will be sent off for polishing. NASA Langley's favorable experience with Gunars Indars at Valley Design is leveraged, and frequent, lengthy technical discussions with the company begin.
    - In the downtime, an all-new test section will be designed and manufactured to prevent further contamination. The new test section will be all-stainless steel, welded inside and out (no interior gaps/seams that can become contaminated). It will be substantially larger in height and width, allowing more room for the two-axis Aerotech traversing mechanism (delivered this month, 11/2010).
    - Programming and integration of Aerotech traverse

- 12/2010
    - Contamination conditions reproduced on a portion of the M5QT electroformed nozzle by running it in the same manner in the test section, without cleaning it. Approximately ¾ of the nozzle interior was masked off with Kapton tape.
    - Valley design begins work developing processes for inspection, polishing, and cleanup of M6QT using the M5QT electroformed nozzle.
- 1/2011
    - Initial inspection photos from Valley Design received. They are using a miniature USB right-angle microscope to take high-magnification photos of the surface not seen before in the throat region.
    - Quote received from Valley Design, having seen the M5QT electroformed nozzle.
    - Status of nozzle mishap and plans given at HRC team meeting in Orlando
- 2/2011
    - New test section design finalized.
    - Quotes solicited and received for all-new stainless steel test section
- 3/2011
    - BME (Bulk Material Equipment) chosen as vendor for stainless test section. Fabrication work begins.
    - Visit to Valley Design to inspect progress on Mach 5 electroformed nozzle.
    - Final requisition for M6QT repair submitted. M6QT nozzle sent to Valley Design
    - Hotwire CVA received from Steve Wilkinson
    - Final-polished Mach 5 electroformed nozzle received from Valley Design. TAMU inspection and preparation for installation
- 4/2011
    - Test section waterjet & welding fabrication complete, picked up from BME in Houston early April, brought to lab for further work.
    - M6QT settling chamber, incoming hose, and remaining parts comprehensively cleaned prior to reinstallation of test section.
    - Final test section hardware additions (accessory mounting plates, door clamps, etc.) welded on. New, better bleed piping provisions installed in exhaust pipe.
    - Test section installed in lab system.
- 5/2011
    - Electroformed Mach 5 nozzle ran several times without issue
    - Mach 6 nozzle received from Valley Design, inspected by TAMU, and reinstalled in the tunnel.
    - Quiet flow readily observed to 140-150 psia on centerline

Final Report FA9550-08-1-0308
Experiments on transition physics in hypersonic boundary layers:
Validation data for modeling and computations

William S. Saric
Texas A&M University, College Station, TX 77843-3141

The Mach 6 Quiet Tunnel (M6QT), the hypersonic low-disturbance facility formerly at NASA Langley, has been permanently installed as part of the Texas A&M National Aerothermochemistry Laboratory (TAMU-NAL) in College Station, Texas. The tunnel now operates interchangeably with the Adaptively Controlled Expansion Mach 5-8 tunnel (ACE) in a blowdown configuration with a maximum runtime of approximately 50 seconds. An initial series of tests to determine the quiet-flow capabilities of the nozzle indicate performance largely consistent with its former operation at NASA Langley, with evidence of a full-length quiet test core at stagnation pressures up to 145 psia. Intermittency present in the pressure signals at total pressures above 80 psia is quantified and discussed. In addition, the capability of the tunnel to support future flared-cone experimental models is demonstrated.

I. Introduction

At hypersonic speeds, aerodynamic heating requires the design of an intricate thermal protection system (TPS) to protect vehicle personnel and payload. Because the aerodynamic heating rates for flow in a turbulent boundary layer are considerably higher than for laminar flow, it is important to be able to predict hypersonic boundary layer transition for the efficient design of the TPS. For decades, progress on the understanding of hypersonic transition estimation and control has been slow and difficult. Deficiencies in knowledge include (a) an insufficient understanding of the relevant instability mechanisms, (b) poor characterization of initial conditions, and (c) lack of validation-quality experimental data.

High costs and heavy instrumentation requirements have prevented the collection of model validation data via flight testing. Wind-tunnel experiments, while more cost effective, have been sparse due to the need for specialized 'quiet-flow' facilities; conventional (noisy) wind tunnels introduce extraneous disturbances into the boundary layer, giving transition results whose trends are contrary to those relevant to flight.

For these reasons, hypersonic vehicles have historically been designed either by using overly simplistic correlations like the Re_θ/M_e method (shown to be a poor choice by Reshotko, 2007), or in a manner that mitigates all uncertainty in the transition location by the gross overdesign of the TPS. This adds unnecessary weight to the vehicle, greatly reducing its useful payload. If efficient hypersonic flight is to become a reality, every effort must be made to maximize the deliverable payload of space vehicles. Minimizing TPS weight is a critical step in doing so, but this can be safely done only after the development of robust physics-based models for transition prediction.

An effort is underway at Texas A&M and universities collaborating under the NASA/AFOSR National Center for Hypersonic Laminar-Turbulent Transition Research to validate and expand the existing analytical framework for our understanding of hypersonic stability. Through this effort, Mack's (1984) linear stability formulation will be expanded to include the additional hypersonic effects of nonequilibrium, thin shock layers, entropy layers, chemistry, and ablation. This work will be incorporated into computational tools including those based on linear stability theory (LST), parabolized stability equations (PSE/NPSE), and direct numerical simulation (DNS). For a proper rigorous study, however, this theoretical and computational work will need quality experimental validation.

The work proposed for the Mach 6 Quiet Tunnel involves a set of foundational hypersonic boundary-layer stability and transition experiments. The goal of these experiments will be to provide validation data for the evolving work in expanding the numerical and theoretical stability framework in the hypersonic regime. The experiments will begin with a mapping of the hypersonic transition parameter space on simple straight and flared conical models, cataloging the dominant instability mechanisms and growth rates for a wide range of parameters such as Reynolds number, surface temperature, surface roughness, angle of attack, and body geometry. Special focus will be given to the coupling between transient growth and roughness. Work will proceed with detailed measurements of receptivity (the establishment of initial growth amplitudes and frequencies), linear and nonlinear mode interactions, and breakdown to turbulence.

In support of these experiments, the Mach 6 Quiet Tunnel has been under reconstruction at Texas A&M and a quiet-flow characterization campaign has been underway. The discussion below describes the infrastructure supporting the recent M6QT installation at Texas A&M, provides a brief review of the tunnel's unique design features, and presents initial quiet-flow performance diagnostics.

II. Facility Description

Infrastructure

The M6QT tunnel facility is installed at the TAMU National Aerothermochemistry Laboratory in College Station, Texas, and is operated in a pressure-vacuum blow-down configuration. Vacuum is supplied by a two-stage Fox-brand Venturi air-ejector system capable of generating a vacuum of 4 torr using approximately 25 kg/sec of compressed air at 150 psia. High-pressure air is provided by two Chicago Pneumatic air compressors (500 SCFM), filtered (99% efficient sub-micron), dried with a twin-tower desiccant drier to -40ºF, and stored in an 820 ft^3 tank at 2400 psia. Air is supplied to the ejector via a 4-inch carbon-steel pipe system, and air to the tunnel is delivered through a 2-inch stainless steel line, heated by a 0.5 MW Chromalox electric-resistance heater (up to 500ºF output), and filtered again, removing 99.9% of particles greater than 1-micron just before entering the tunnel. Both pipelines are controlled by a combination of Bray pneumatic actuators, which start and stop the ejector and tunnel systems, and a series of Stra-Val regulators that provide the correct control pressure to the ejector system and the desired stagnation pressure to the tunnel.

In its early shakedown installations in 2008 and 2009, the M6QT operated in the TAMU-NAL interchangeably with the Adaptively-Controlled Expansion (ACE) Mach 5-8 tunnel. In this arrangement, one tunnel would be removed from the infrastructure for months at a time to allow the other to complete a test campaign. As of November 2009, this has been significantly improved with the conclusion of a major construction project allowing both the ACE Mach 5-8 Tunnel and the M6QT to be permanently installed in the same laboratory and share the same pressure-vacuum infrastructure. The vacuum from the ejector system is supplied to either tunnel by using a pair of 24″-diameter actuated knife gate valves, and pressure is supplied to either tunnel using a pair of 3″ manual ball valves downstream of the 1-micron particle filter. With these improvements, it is now possible to switch between active facilities in a matter of minutes by the simple toggling of valves, minimizing facility downtime and maximizing experimental productivity and repeatability.

To achieve the typical operating total temperature of 350ºF [450K], the M6QT is preheated convectively prior to a run by running air through the tunnel at a total pressure of 50 to 100 psia without activating the ejectors. With the 500 kW pre-heater active, this process takes 15-20 minutes for the first run of the day. For subsequent runs, the preheating process takes less time, as the tunnel supply piping and settling chamber are fully insulated with 2″-thick fiberglass insulation blankets and retain their heat well throughout the day. Further, 8 kW of direct heating on the settling chamber is provided by Ogden Mighty-Tuff electric-resistance band heaters and a Chromalox 3340 closed-loop controller in order to maintain the high-thermal-inertia settling chamber at 350ºF, which greatly reduces preheating requirements.

Tunnel run time is largely governed by the high mass flow requirements for the ejector. In a maximum-runtime configuration where excess pressure in the 2-inch line is diverted to the 4-inch line through an actuated bypass valve, a full run at constant stagnation pressure of either tunnel can last up to 50 seconds. With this 50-second run time, the M6QT is a unique long-duration, hypersonic quiet-flow facility. The long-duration capability of the facility will enable the acquisition of several detailed velocity profiles within the boundary layer per run with a high-resolution hotwire traversing mechanism.

Quiet Flow Features

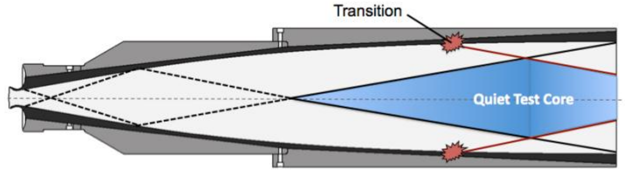

Figure 1: Nozzle quiet test core location (notional scale)

In a conventional (or "noisy") hypersonic wind tunnel facility, turbulent eddies in the nozzle-wall boundary layer radiate pressure disturbances into the test area along mach lines, producing a high-noise environment unsuitable for many stability and transition experiments. A quiet nozzle aims to initiate and preserve a laminar nozzle-wall boundary layer to create a region of uniform, quiet flow free of these disturbances. For an axisymmetric quiet nozzle like the M6QT, this "quiet test core" is a double-cone in shape, bounded upstream by the conical boundary for uniform flow at the exit Mach number, and bounded downstream by the cone created by the pressure disturbances radiating inward from the turbulent nozzle wall at the Mach angle. A diagram of the M6QT quiet core is presented as Figure 1.

The Mach 6 Quiet Tunnel, designed at NASA Langley and moved to Texas A&M in 2005, leverages a number of unique design features to achieve a quiet test core of a useful size. The nozzle itself is 39.76″ in length with a 1″ throat diameter and 7.5″ exit diameter.

Quiet flow features of the M6QT begin with flow conditioning in the settling chamber; two rigid mesh flow spreaders facilitate the expansion of the incoming pipe flow to the 11.5″ settling chamber inner diameter, a perforated steel plate attenuates valve noise upstream, and a series of seven screens of increasing mesh density encourage flow uniformity by reducing mean-flow streamwise vorticity. These components are pictured in Figure 2.

Figure 2: Settling chamber flow conditioning

Just upstream of the nozzle throat, the turbulent boundary layer in the settling chamber and subsonic approach is extracted through an annular bleed slot to begin a new laminar boundary layer on the nozzle (Figure 3). A simple toggling of actuated ball valves between bleed-valve-open (BVO) and bleed-valve-closed (BVC) states enables exclusive control of the quiet vs. noisy status of the test area. This can be done several times throughout the course of a single run, if desired for comparative studies.

In order to maintain the laminar nozzle-wall boundary layer initiated by the bleed slot, the nozzle's contour design, contour accuracy, and surface finish were all given special attention during the design and manufacturing processes. The contour is of a slow-expansion design with a straight-wall section to minimize nozzle-wall curvature and delay the growth of Görtler vortex instabilities (Saric 1994). The nozzle interior was manufactured by electroforming pure nickel onto a precision stainless steel mandrel in order to maximize surface contour accuracy and minimize waviness. In addition, the nozzle interior was later plated with a nickel-phosphorus alloy to improve corrosion resistance and to enhance the ability of the surface to be finely polished (< 0.8 μm p-p, $Re_k < 10$) at the throat. To prevent damage to this surface, a one-micron particle filter is installed just upstream of the settling chamber. Additional detail regarding M6QT flow quality features is available in Wilkinson (1997).

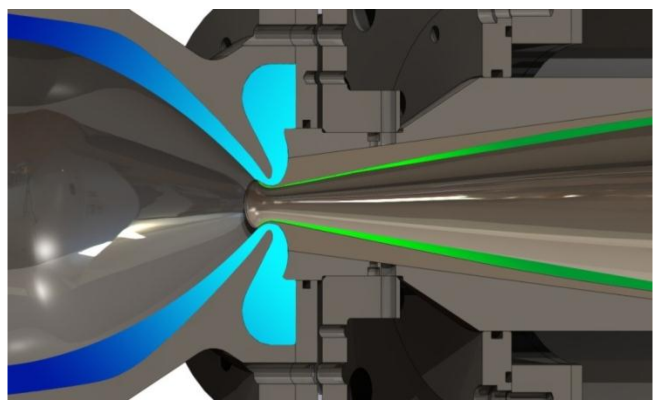

Figure 3: Cross-section of bleed slot and plenum between subsonic approach and nozzle throat

Test Section

A new steel test section was designed and constructed in October 2008 in preparation for the first installation of the facility. The design is similar to the original Langley test section in that it is of an enclosed-free-jet configuration. The box interior cross-section is 21″ square, with the corners set in to create an octagonal shape for stress relief. All walls are 0.5″ thick structural steel. Two 13″ x 22″ side doors and an identical ceiling panel are 1.0″ thick and are fully interchangeable. Each side door is currently fitted with 6″ diameter dual-surface optical flats for visual access to the free jet aft of the nozzle exit for schlieren imaging. Six 5.5″ diameter accessory ports are available to provide non-destructive penetration of the box for instrumentation. The test section can accommodate either of two Mach 5 pilot nozzles or the Mach 6 nozzle, requiring only that the axial position of the diffuser catcher be moved forward for Mach 5 operation. In the Mach 6 configuration, there is sufficient working area surrounding the free jet to accommodate the installation of a three-axis probe traversing mechanism, under active development now.

III. Nozzle Centerline Quiet Flow Performance

Following the reactivation of the M6QT in the parallel infrastructure at the TAMU-NAL, a series of tests were conducted to assess the quiet flow performance of the tunnel as measured by dynamic pressure transducers located on the nozzle centerline. The probes were mounted into a machined stainless steel conical tip mounted to a rigid stainless steel tube with 0.562″ OD and 0.120″ wall thickness. Tubes up to 32″ in length were used, allowing the sensor to be easily positioned on the nozzle centerline at any axial location between X = 20.76″ (the onset of uniform Mach 6 flow and the upstream boundary of the quiet core) and X = 41″. Data of primary interest were taken with the probe positioned directly at the center of the nozzle exit plane (X = 39.76″), as this is the location often used for quiet-flow performance quoted in the tunnel's previous installation at NASA Langley.

The following sections describe in detail the instrumentation and support equipment used in this campaign, and proceed to present representative data from several key runs to illustrate the M6QT's quiet flow envelope as it is currently known.

Kulite dynamic pressure sensors

High-frequency pressure sensors manufactured by Kulite Semiconductor were used to measure Pitot pressure fluctuations at various axial positions on the nozzle centerline. Sensors used were the XCEL-100-5A or XCEL-152-10A models. Basic data on each sensor are presented in Table 1.

Table 1: Key specifications of Kulite dynamic pressure sensors used for quiet flow diagnostics

Sensor	**Mode**	**Range**	**Casing Diameter**	**Natural Frequency**	**Typical Noise Floor** (rms P'/P)
XCEL-100-5A	Absolute	5 psia	0.101″	150 kHz	0.06 %
XCEL-152-10A	Absolute	10 psia	0.152″	175 kHz	0.25 %

The Kulite sensors used initially were of the 5 psia range variety, and were found to have an excellent signal-to-noise ratio, with a demonstrated ability to resolve pressure fluctuation levels as low as 0.06% rms P_{t2}'/P_{t2}. However, significant robustness issues were encountered with these units, wherein they would frequently be destroyed during the tunnel unstarting process at the end of a run. As for most of Kulite's silicon-diaphragm sensors, these 5 psia units are rated for burst overpressure at three times their full-scale rating, or in this case, 15 psia. When the tunnel's vacuum ejector is deactivated at the end of a run, and the unstart shock travels upstream through the system, the pressure on the sensor rapidly returns to atmospheric pressure – this strong, rapid impulse loading back to the rated burst pressure of the Kulites would break them, particularly when unstarting the tunnel from total pressures above 60-70 psia.

As a result, XCEL-152-10A Kulites with 10 psia full-scale (and thus 30 psia burst) ratings were used. With their thicker diaphragm, these units were found to be much more robust, and never broke during or after a run. However, due to their sensitivity being half that of the 5 psia units, and perhaps due to their physically larger size, the signal-to-noise ratio was considerably less, reading RMS pressure fluctuation levels of not less than 0.25%. Although this lies considerably above the generally-accepted 0.10% threshold for flow considered "quiet," an order of magnitude still separates the quiet and noisy RMS levels, and the difference is still very clearly delineated. The data obtained in this portion of the campaign are therefore to be considered only as binary indicators for the presence of quiet flow, and not quantitative measurements of its amplitude.

Signal conditioning and data acquisition

The Kulite sensors were connected using fully-shielded cabling to an Endevco Model 136 power supply and amplifier unit. This device supplies a steady 10V excitation to the Kulite, and amplifies the signal 100 times, from its inherent 100 mV full-scale output to 10V. The signal amplifier in the Endevco Model 136 has a 200 kHz bandwidth, quoted at a -3dB rolloff.

The amplified signal output from the Endevco unit was then connected to a Kemo VBF44 4-Channel Laboratory Electronic Filter for analog antialiasing filtering and DC component removal. The signal was first processed by two Kemo filter channels configured for low-pass filtering at either 100 or 200 kHz. This signal was then separately sent to the data acquisition system and to a second bank of filters operating at a high-pass frequency of 10 Hz and applying an additional amplification of 30 dB (31.6x). This AC-only, re-amplified signal was sent to a second channel on the data acquisition system for better resolution within the noise level.

Data acquisition was performed using a PC equipped with a National Instruments PCI-6122 data acquisition card and driven by a custom LabVIEW 2009 VI. This card has four channels, each with 16-bit resolution and fully independent analog-to-digital converters. Sampling was performed at either 200 kHz or 400 kHz (2x the low-pass frequency). At these high sampling frequencies, the simultaneous-sampling capability of the PCI-6122 avoids channel crosstalk effects common with multiplexing DAQ cards.

Initial observation of quiet flow

A Kulite Pitot pressure trace from the first run with observed quiet flow is presented below in Figure 4. For this run, the Kulite sensor head was located at X = 26.76″ (or 13″ upstream of the nozzle exit), and the total pressures were relatively low (P_o = 55 psia with BVC, 45 psia with BVO). Total temperature was 430K.

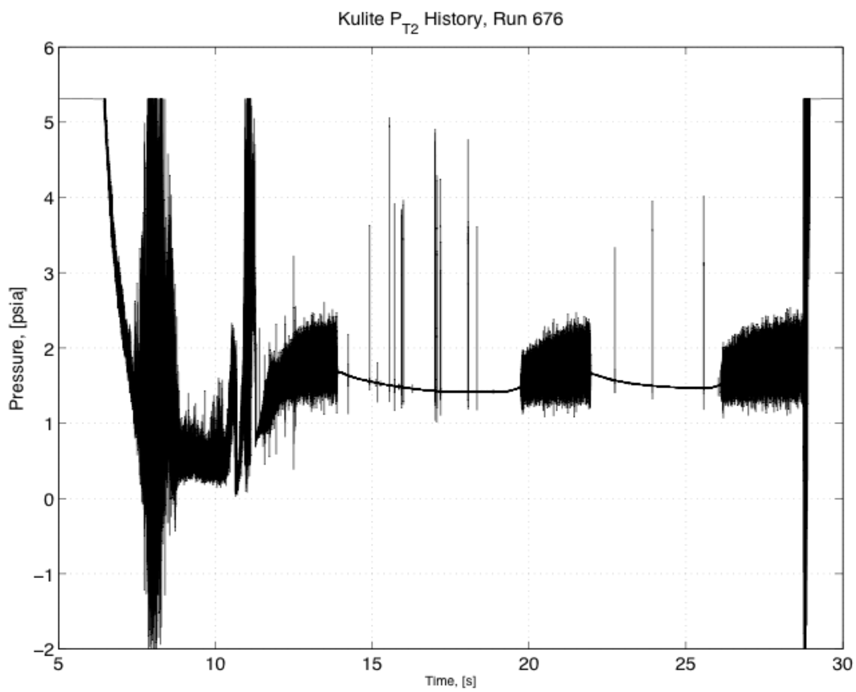

Figure 4: Kulite Pitot pressure trace, Run 676. P_o = 55 psia (BVC), 45 psia (BVO). T_o = 430 K

With the bleed valves open (14-19.5 seconds, 22-26 seconds), the nominal rms Pitot pressure fluctuation was observed to be P_{t2}'/P_{t2} = 0.08% − essentially this sensor's electronic noise floor under no-flow conditions. With bleed valves closed (19.5-22 seconds, 26-29 seconds), these levels were approximately 2.5-3.0%. It is also noteworthy that under quiet-flow conditions, the Mach number was observed to rise from 5.82 to 5.91, evidence of the thinner laminar boundary layer and the resulting slightly larger expansion area ratio.

Following this run, several more were completed with the goal of incrementally moving the Kulite further aft to the nozzle exit plane (X = 39.76″) and eliminating intermittencies at these low pressures. These were both readily accomplished with a new sharp-wedge probe support to replace the original blunt cylindrical support, a cleaning of the nozzle throat & contraction region, and by preheating the tunnel further to operate at 450K.

Determination of upper pressure limit for quiet flow

Run 724, for which a pressure trace is shown in Figure 5, was conducted to determine the upper-limit pressure for quiet flow with the measurement location positioned at the exit plane (now using a 10 psia Kulite). The settling chamber temperature was held constant at 450K, and the settling chamber pressure was gradually increased from a starting pressure of 70 psia to 145 psia with bleed valves open. The Kulite pressure trace in Figure 5 shows the immediate drop in pressure fluctuation levels when the bleed valves were opened at 19.5 seconds. Then, only a few intermittent spikes are encountered until 32.5 seconds, when the spikes become much more prevalent as the total pressure is increased through 115 psia up to 145 psia at 38.5 seconds, when bleed valves are closed again.

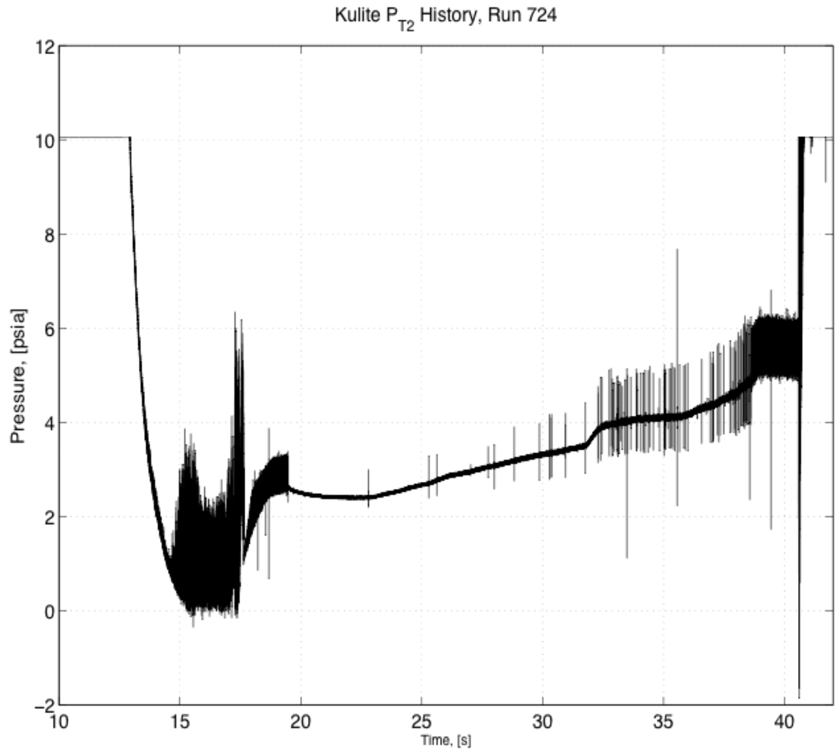

Figure 5: Kulite Pitot pressure trace, Run 724. P_o = 70-145 psia (BVO). T_o = 450 K

A detailed view of a representative spike is shown in Figure 6. The profile is typically characterized by an exponential rise in pressure, an immediate decrease below the nominal Pitot pressure, and an exponential recovery back to the nominal pressure. This profile occurs in approximately 1-2 ms, and directly follows the general character of the sound-mode disturbances described in Blanchard (1997) as observed in constant-voltage anemometer (CVA) hotwire signals.

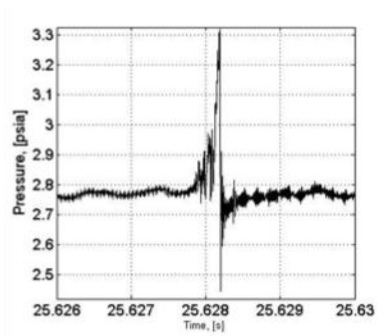

Figure 6: A representative intermittent pressure spike

To quantify the variation in the occurrence density of these intermittencies, an ‘intermittency factor’ was defined as the percentage of moving-RMS windows (2 ms wide) within a larger traveling window (1000 ms wide) found to contain an RMS level greater than a threshold. The moving RMS and intermittency factor are plotted together for this run in Figure 7. Here, it is seen that even at the point of highest apparent spike density (at P_o = 145 psia, 38 seconds), the intermittency factor indicates that only approximately 6% of 2-ms windows contain these discrete pressure fluctuations.

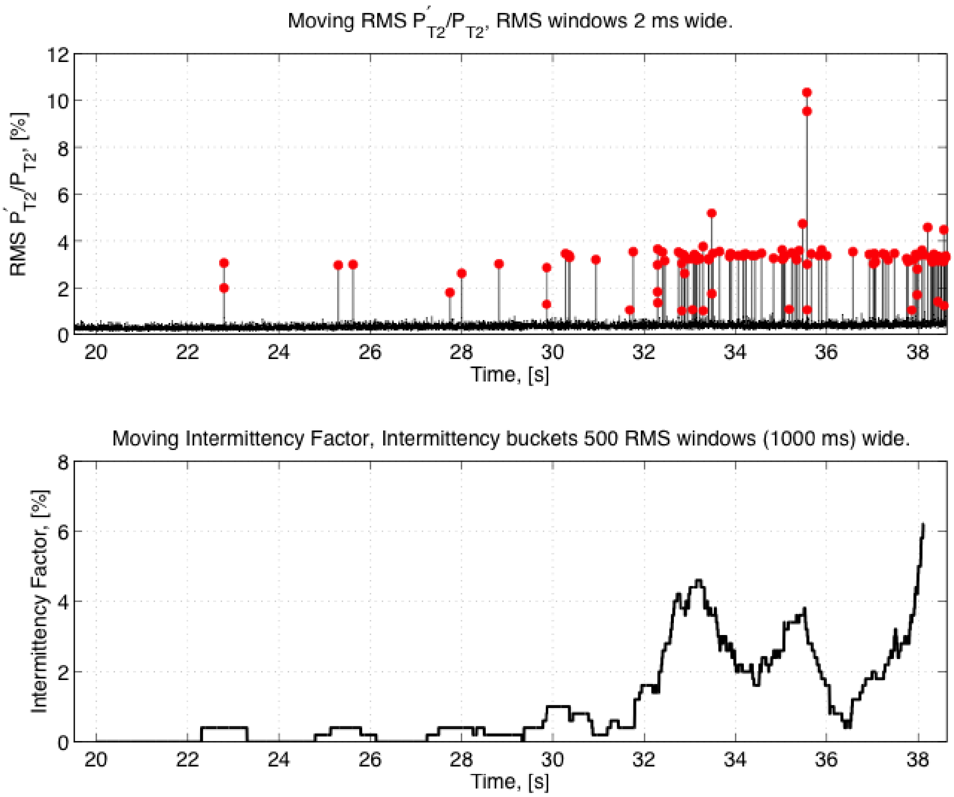

Figure 7: Moving RMS and Intermittency Factor, Run 724. P_o = 70-145 psia (BVO). T_o = 450K

Another interesting way to visualize the present performance of the M6QT as compared with Langley performance is to directly compare the present Pitot-pressure time histories with the selected uncalibrated hotwire time histories presented in Wilkinson (1994). Figure 8 below shows this comparison. Note that the time histories are both spike-free at 80 psia, with low levels of intermittency by 130 and 140 psia. At 145 psia, however, the NASA Langley time history indicates a very dense concentration of intermittencies, while the TAMU performance still indicates a low level (again, 5-6%) presence of intermittencies.

The very selective time histories shown in this figure are not presented to imply an expectation of performance exceeding that at NASA Langley, but rather to solidify the notion of low intermittency-density and provide confidence that the present performance is at least comparable to that at the tunnel’s installation at NASA Langley.

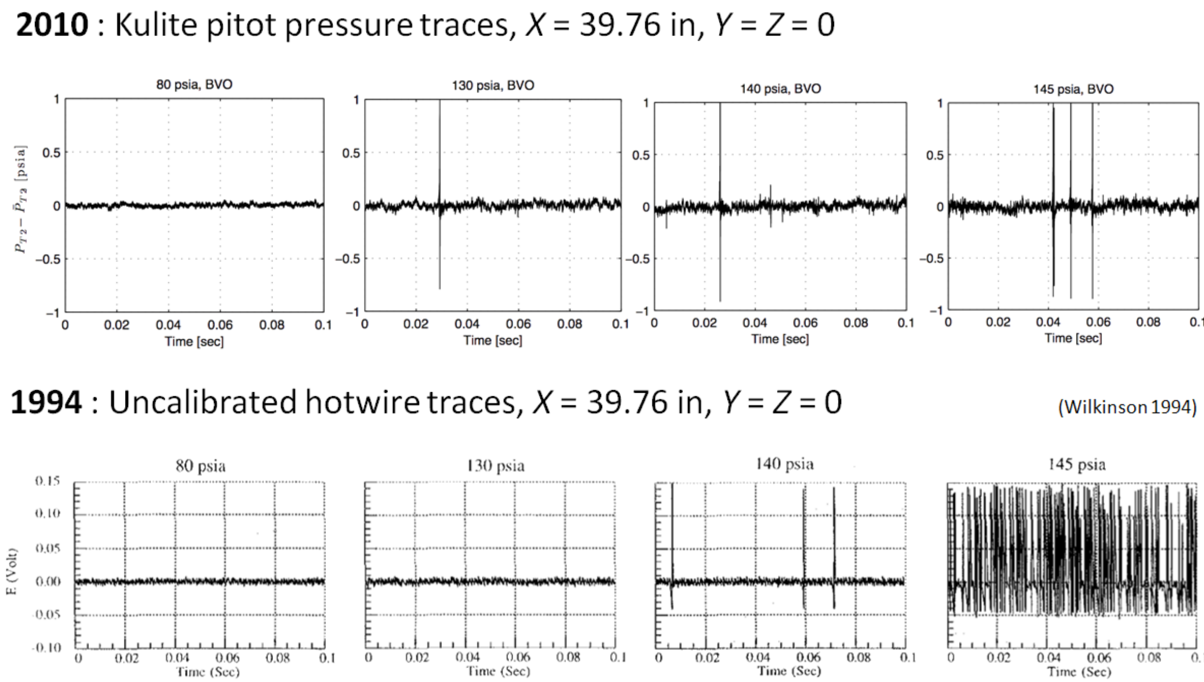

Figure 8: Selected nozzle-exit centerline time history comparisons with 1994 hotwire data. Run 724. P_o = 80-145 psia (BVO). T_o = 450K.

Quiet flow performance at constant stagnation pressure near upper limit

A Pitot pressure trace from the next run of interest, Run 727, is shown in Figure 9. For this run, the tunnel was immediately started to a settling chamber pressure of 130 psia, and allowed to stabilize with bleed valves open for the duration of the run. Here, it can clearly be seen that at constant pressure, the intermittency density strongly decays with run time. The corresponding moving RMS and intermittency factor charts in Figure 10 confirm this – although the density starts much higher (25%) than observed at the end of the pressure sweep in Run 724, the intermittency decays to nearly zero by the end of the run. In fact, between approximately 24 and 26 seconds, nearly 2 seconds of uninterrupted quiet flow is indeed observed. This decaying-intermittency behavior has been reliably repeated on many subsequent runs. There has been speculation that the intermittent behavior may be related to nozzle-throat heating, whereby as the nozzle throat area heats under started flow conditions, local roughness Reynolds numbers are reduced and surface imperfections introduce. This is to be investigated, and, if this is confirmed to be the cause, supplemental nozzle-throat heating may be considered.

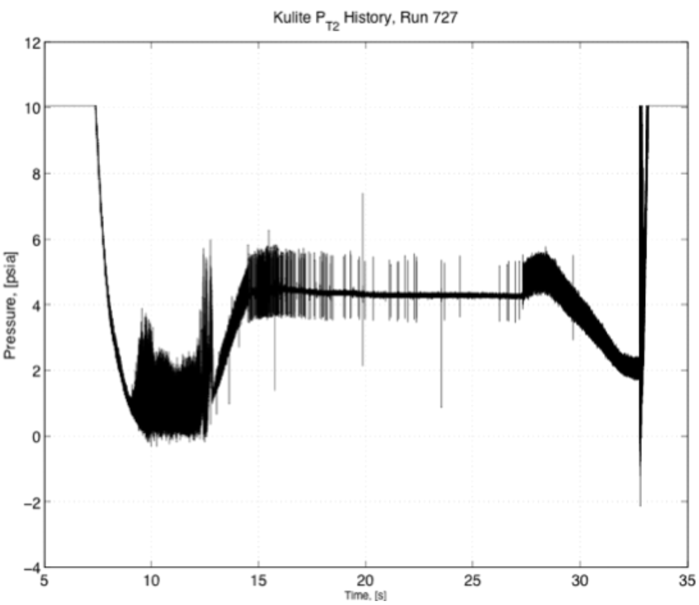

Figure 9: Constant pressure P_o = 130 psia, T_o = 450K

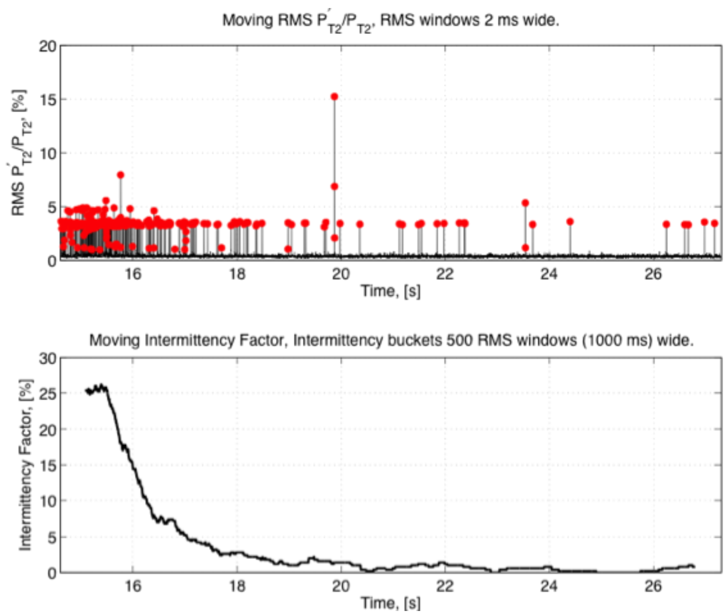

Figure 10: Moving RMS, Intermittency Factor, Run 727

The present 130 psia pressure level is the historically-quoted upper-pressure limit for intermittency-free quiet flow in the M6QT's installation at NASA Langley. Considering the continuous runtime capability the M6QT had at its former location, it is feasible that even the intermittencies currently observed in the first 10-15 seconds of a constant-pressure 130 psia run may be consistent with NASA Langley-era performance. Nevertheless, in the current infrastructure with limited runtime, the intermittencies may prove a challenge. As such, their causes and experimental impact are both being thoroughly investigated now.

IV. Flared Cone Model Tests

Following the successes with the reinstallation of the M6QT, parallel infrastructure construction, and the initial quiet flow campaign, it was desired to briefly demonstrate the capability of the M6QT to support the flared-cone test articles that will soon be used as the primary platform for its initial stability & transition experiments. In May 2010, the NASA Langley 93-10 cone was installed in the M6QT for this purpose.

The 93-10 geometry consists of a 5º half-angle straight cone section for the first 10″ of axial distance, followed by a tangent flare of radius 93″ until the base of the cone at the 20″ station. The base diameter is 4.6″. The 93-10 is instrumented with arrays of 21 pressure ports and 43 thermocouples axially distributed along the length of the cone, separated by 180º azimuthally. The model is nominally 0.070″ thick, and is 0.030″ thick along the thermocouple axis. A photograph of the Langley 93-10 cone installed in the Mach 6 Quiet Tunnel is shown in Figure 11. The cone was installed such that the base plane of the cone was 2.8″ downstream of the nozzle exit plane. In this position, the sharp tip of the cone was located approximately 5.1″ downstream of the upstream tip of the quiet test core (or from onset of uniform flow). It was later discovered that Langley typically ran the model with the cone base 4.0″ downstream of the exit.

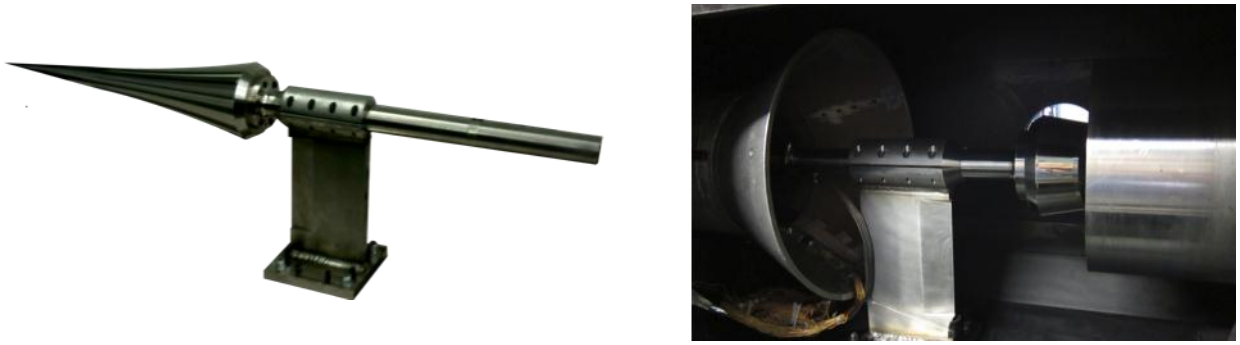

Figure 11: NASA Langley 93-10 flared cone model, on bench (left) and installed in M6QT (right)

For these initial, very basic diagnostic tests, the cone's embedded pressure ports and thermocouples were inactive, and the only diagnostic was a continuous-light-source schlieren set up at the exit of the nozzle as a basic indication of started flow. Figure 12 shows two schlieren images taken during a run conducted near the maximum quiet flow pressure. The images are averaged from 8 frames each. Indeed, one can clearly see a boundary layer on the cone body and an expansion wave at the base both with bleed valves closed (P_o = 138 psia) and bleed valves open (P_o = 130 psia). The single discernable difference between the two configurations is the presence in BVO case of a recompression feature emanating from the shoulder of the cone at the conclusion of the expansion wave.

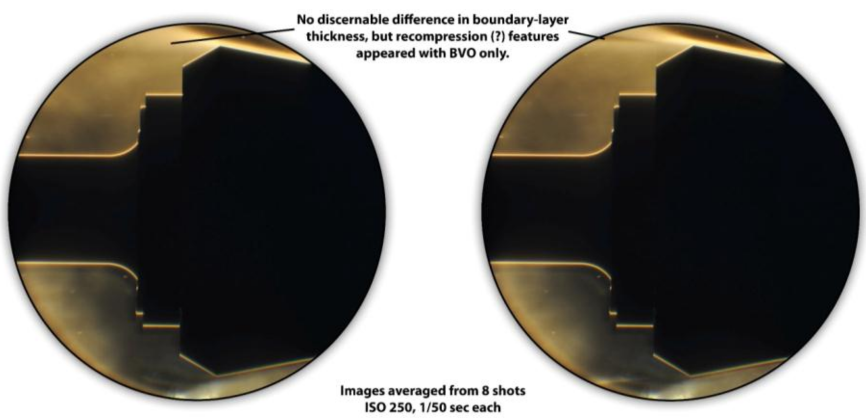

Figure 12: Langley 93-10 cone schlieren images;
BVC, P_o = 138 psia (left) ; BVO, P_o = 130 psia (right)

The important but very simple conclusion of this test was that indeed the tunnel was able to start with the cone blockage in place. In fact, with the cone further inside the nozzle than perhaps it needed to be, one might consider this test conservative, with the tunnel starting for blockage *more severe* that we will expect experimentally. This test, of course, does not consider the blockage due to the planned probe traversing mechanism, but this is being designed to have a minimal impact and will be fully evaluated soon.

V. Future Work

Future work will begin with a more-comprehensive assessment of flow quality. Kulite and hotwire probes will be mounted to a three-axis traversing mechanism (now under design & construction) and translated throughout the quiet test core, establishing contours of both Mach number and noise level. This campaign will aim to reproduce the work completed by Blanchard at NASA Langley (1997) and fully verify the performance of the Mach 6 Quiet

Tunnel as installed at Texas A&M. It is only after this is accomplished with confidence that valid stability and transition experiments can proceed.

Initial experiments will be conducted in order to acquire high-resolution, high-accuracy code validation data for improved understanding and modeling of the basic laminar-turbulent-transition physics associated with hypersonic boundary-layer flows with wall roughness. Straight and flared cones previously used at NASA Langley and Purdue University will initially be used. Hotwire and hotfilm anemometry, high-frequency pressure diagnostics, and surface thermocouple measurements will be used to obtain mean and disturbance quantities in the mean flow, in the boundary layer, and on body surfaces.

VI. Summary

The reactivation of the Mach 6 Quiet Tunnel within the infrastructure of the National Aerothermochemistry Laboratory at Texas A&M University has been completed. Preliminary dynamic Pitot pressure data indicate performance largely consistent with that in the tunnel's former installation at NASA Langley, and the capability of the tunnel to support the blockage of the initial experimental flared-cone models has been verified.

Now restored to operational status as a unique long-duration hypersonic quiet wind tunnel, the M6QT at Texas A&M is a keystone feature of the NASA/AFOSR National Center for Hypersonic Laminar-Turbulent Transition Research[1].

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[1] See `http://hypersonics.tamu.edu/`